

# **Gamma-Ray Burst Arrival-Time Localizations: Simultaneous Observations by Ulysses, Pioneer Venus Orbiter, SIGMA, WATCH, and PHEBUS**

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## ABSTRACT

Between the launch of the Ulysses spacecraft in 1990 October and the entry of Pioneer Venus Orbiter (PVO) into the atmosphere of Venus in 1992 October, concurrent coverage by Ulysses, PVO, the WATCH experiments aboard the Granat and EURECA spacecraft, and the SIGMA and PHEBUS experiments aboard the Granat spacecraft was obtained for numerous gamma-ray bursts. 15 of them were detected by 3 or more instruments on spacecraft separated by distances of several AU, and could therefore be accurately localized by triangulation. In some cases independent, accurate locations were obtained by SIGMA and/or WATCH. We present these localizations, which range in area from 0.9 to 530 arcminutes<sup>2</sup>.

*Subject headings:* gamma-rays: bursts

## 1. Introduction

A knowledge of the precise locations of cosmic gamma-ray bursts (GRBs) is important for many studies. When obtained rapidly, they allow multi-wavelength counterpart searches to be carried out, which have led to the discovery of fading radio and optical counterparts. After days to months, these fading counterparts are unlikely to be detected, but precise locations, even obtained years later, are useful for statistical studies, such as clustering, searches of cataloged objects for possible associations, and host galaxy limits. A number of GRBs have had their redshifts spectroscopically measured or constrained (e.g., Metzger et al. 1997; Kulkarni et al. 1998; Djorgovski et al. 1998), and the results establish a cosmological origin for them, i.e.  $z \gtrsim 1$ . More recently, however, one burst has been shown to be spatially and temporally coincident with a nearby supernova (Galama et al. 1998), indicating that GRBs may be a diverse phenomenon, and that their counterparts may not all be faint galaxies which would be difficult to discern at late times in a relatively large error box. This paper is the fifth in a series presenting GRB localizations by triangulation between spacecraft in the 3rd Interplanetary Network (IPN), which are separated by several thousand light-seconds. The first two presented results obtained with the *Ulysses*, Compton Gamma-Ray Observatory, and Pioneer Venus Orbiter (PVO) or Mars Observer spacecraft (Laros et al. 1997, 1998). The third and the fourth are the *Ulysses* supplements to the BATSE 3B and 4Br catalogs (Hurley et al. 1999a,b). This paper presents results obtained with the *Ulysses*, PVO, Granat, and EURECA spacecraft. The Granat experiments involved were WATCH, PHEBUS, and/or SIGMA. The EURECA experiment was WATCH.

## 2. Instrumentation

All of the instrumentation used to obtain the data presented here is based on scintillation crystals, and all the instruments have been described in detail elsewhere. We

review each briefly.

The *Ulysses* GRB detector (Hurley et al. 1992) consists of two 3 mm thick hemispherical CsI scintillators with a projected area of about 20 cm<sup>2</sup> in any direction. Its nominal energy range is 25-150 keV. GRB time histories are recorded with time resolutions which range from about 8 ms (in a triggered mode) to 0.5 - 2 s (in real time modes). The detector is mounted on a magnetometer boom far from the body of the spacecraft, and has a practically unobstructed view of the full sky. The *Ulysses* orbit is heliocentric, with a 5 AU aphelion. The instrument has no inherent burst localization capability.

PVO had two burst detectors, consisting of 3.8 cm diameter by 3.2 cm long CsI scintillators, operating in the 100-2000 keV energy range. Time histories were recorded with resolutions ranging from 1/4096 s in time-to-spill mode, to 12/1024 s in triggered mode, to 16 s in real time mode. The spacecraft was in orbit around the planet Venus for the observations reported here. Like the *Ulysses* detector, it had no inherent directional capability. Further details may be found in Klebesadel et al. (1980).

The SIGMA telescope was a coded mask imaging system capable of localizing sources to arcminute accuracy within the fully coded field of view. However, the bursts described in the present paper were observed in the sidelobes, and the images were partially coded, leading to accuracies in the 10's of arcminutes range and above. The localization procedure is described in Claret et al. (1994). GRB time histories were generally recorded by the SIGMA anticoincidence system, which operated in the energy range above several hundred keV (the precise threshold for any given photon interaction depends on the location of the interaction in the shield). The time resolution was variable, depending on the count rate (time-to-spill mode) but typically was around 100 ms and greater. SIGMA was mounted on the Granat spacecraft, which was in a highly eccentric Earth orbit with apogee > 70000 km.

The WATCH instrument was also aboard the Granat spacecraft. Based on a novel

rotating modulation collimator technique, the WATCH detectors surveyed 80% of the sky, and localized bursts to elliptical error boxes, which may be approximated by circles whose  $3\sigma$  radii are 0.2 - 1.6 °. The localization accuracy depends, among other things, on the accuracy with which the attitude of the Granat spacecraft can be reconstructed. In general, the spacecraft attitude was derived from the star tracker, which was part of the SIGMA instrument, and when it was operating the uncertainties were negligible as far as the burst locations in this catalog are concerned. However, WATCH detected some bursts at times when SIGMA was off, and only the predicted spacecraft attitude is known. The spacecraft actually oscillates slowly about this predicted position, with peak-to-peak amplitudes of 30 - 40 ', independently about three axes. In these cases, the attitude was reconstructed by fitting the positions of bright X-ray sources in the WATCH data for periods approximately 30 m long about the time of the burst. This procedure recovers the secular drift associated with solar motion, but not the oscillations, and a systematic uncertainty of 0.5 ° was assumed to account for them. The energy range was 8 - 150 keV and the time resolution ranged up to approximately 0.8 s. WATCH/Granat is described in Sazonov et al. (1998). A similar instrument was also launched later aboard the EURECA spacecraft into low Earth orbit (Lund, 1985).

Finally, the PHEBUS experiment was also included in the Granat payload (Barat et al. 1988; Terekhov et al. 1991), consisting of six 12 cm. long by 7.8 cm. diameter BGO detectors oriented along the axes of a Cartesian coordinate system, and operating in the 100 keV - 100 MeV energy range, with 1/128 s to 1/32 s time resolution. By comparing the count rates of the various detectors, it is possible to obtain an approximate source location; the accuracies vary depending on the burst, but are in the several 10's of degrees range and above. Although quite coarse, this information proved to be very valuable for some of the bursts described here (see below). The spacecraft attitude uncertainties discussed above are negligible compared to the PHEBUS localization uncertainties.

At the time the bursts in this catalog were detected, the interest in providing small error boxes rapidly was recognized. However, the mission designs, in some cases already 15 years old, did not always allow for this. Nevertheless, in three cases (GRB910219, GRB911016, and GRB920714) localizations were done rapidly enough to allow imaging of the fields down to 18th magnitude within three days, although no optical counterparts were found (Castro-Tirado et al. 1994).

### 3. GRB Localization

The precise error boxes presented here have been derived by triangulation, or arrival-time analysis between widely separated spacecraft. (“Widely separated” here means distances of several AU.) This method consists of analyzing the time histories of a GRB as recorded by two spacecraft in order to determine the most likely time difference and its statistical uncertainty. This analysis is done using a  $\chi^2$  statistic (e.g. Hurley et al. 1999a; Laros et al. 1997). There is, however, an important difference between the events presented here and those presented in previous catalogs, which requires further explanation.

GRB time histories are energy-dependent. A time history taken in the 25-100 keV *Ulysses* energy range may differ from that taken in the PVO 100-2000 keV range. The magnitude of this difference varies considerably from event to event, and can easily be judged in, say, the  $\chi^2$  technique (Hurley et al. 1999a), where the goodness-of-fit is reflected in the value of  $\chi^2$  per degree of freedom. When the “fit” between two time histories is poor, the estimate of the statistical uncertainty in the time difference may become unreliable. This, in turn, renders the annulus width estimates, and hence the confidence value for the error box, suspect. In previous GRB location catalogs, we have been able to avoid this problem by comparing time histories in the same, or very similar energy ranges. Thus in the *Ulysses* /BATSE catalogs, 25-150 keV *Ulysses* time histories were compared to 25-100 keV

BATSE time histories, and the fits were generally satisfactory (Hurley et al. 1999a,b). In the *Ulysses* /BATSE/PVO catalog, the 25-150 *Ulysses* time histories were again compared to the 25-100 keV BATSE time histories, but the 100-2000 keV PVO time histories were compared to the >100 keV BATSE time histories.

In the present catalog, we have four instruments - *Ulysses* , PVO, PHEBUS, and SIGMA - which recorded their time histories in a single energy range which was different from all the others. Some of these energy ranges, e.g. *Ulysses*' and SIGMA's, do not even overlap. We have therefore used the following techniques to assure that the error boxes are conservatively estimated. First, we have used the PHEBUS 100 keV - 100 MeV time history for the comparisons instead of the SIGMA one (every SIGMA event in this catalog was also observed by PHEBUS). Second, we perform the following internal consistency check.

Let  $\delta T_{i-j}$  be the difference in arrival times between spacecraft  $i$  and spacecraft  $j$ . Let the subscript  $c$  denote the calculated values, and  $t$  the true values, unknown to the experimenter. Then for a network of three spacecraft,  $\delta T_{1-2,t} + \delta T_{1-3,t} + \delta T_{3-2,t} \equiv 0$ . In general, the sum of the calculated values will not be zero, due to a combination of statistical and systematic errors:  $\Delta \equiv \delta T_{1-2,c} + \delta T_{1-3,c} + \delta T_{3-2,c} \neq 0$ . Let  $\sigma(\delta T_{i-j})$  be the statistical error associated with  $\delta T_{i-j,c}$ . (We have shown in Hurley et al., 1999a, that the error distribution should be approximately normal). In those cases where  $\Delta$  is incompatible with the values of  $\sigma(\delta T_{i-j})$ , we increase them appropriately.

Finally, we note that the events in this catalog were all observed by just three widely separated spacecraft. Triangulation therefore yields two possible intersection points for the annuli. We have generally used the localization capabilities of WATCH and SIGMA to identify the correct intersection. In those cases where no WATCH or SIGMA data was available, we have used the PHEBUS location capability to identify the intersection.



#### 4. GRB Locations

Table 1 gives the dates and times of the bursts and identifies the spacecraft which observed them and their operating modes. In some cases, bursts were observed by additional near-Earth spacecraft, such as DMSP (The U.S. Air Force Defense Meteorological Satellite Program: Terrell et al. 1998). These data were consistent with those of other near-Earth spacecraft, however, and their use did not constrain the error boxes further. Also, some events were localized to two alternate error boxes which could not be distinguished using the directional response of any of the instruments. These are not discussed further<sup>2</sup>. This table also indicates which bursts were observed when the SIGMA star tracker was off and the spacecraft attitude could not be precisely determined, as discussed above.

For the bursts in Table 1, Table 2 gives the corners of the error box, the center of the error box, its area, and its maximum dimension. The epoch for the coordinates is J2000. In general, the smallest possible error box derived from triangulation using 3 spacecraft will be defined by 4 or 6 corners from the intersection of 3 annuli (depending on the width of the annuli), but in some cases, as noted below in Table 2 and the figure captions, grazing intersections may reduce this number. The coordinates have been corrected to the heliocentric frame (the equivalent of the aberration correction - see Hurley et al. 1999a), and supercede all previous data on these bursts. Some of the error boxes are shown in figures 1 through 7. In two cases the WATCH and IPN annuli are only marginally compatible (figures 4 and 6); it is thought that the cause is 1) the imprecisely known Granat spacecraft attitude, which may result in a systematic underestimate of the total WATCH error circle radius, and/or 2) the approximation of the elliptical WATCH locations by circles.

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<sup>2</sup>Full details of these events in particular, and all bursts in general localized by the IPN, may be found at <http://ssl.berkeley.edu/ipn3/index.html>.

## 5. Conclusions

IPN error box areas are comparable in size to, or in some cases much smaller than those that can be derived rapidly from wide field X-ray cameras such as the one on board BeppoSAX ( $\approx 10'$  error circle radius - e.g. Costa et al 1997). For most of the events in this catalog, the initial error boxes were circulated to the astronomical community with delays which were considerably greater than those that can be achieved by BeppoSAX. However, the fact that fading optical transients can be detected in the BeppoSAX wide field camera error circles even several days after the burst means that an IPN which can deliver small error boxes on  $\approx$  day timescales will be useful for counterpart identifications. Such a network now exists, consisting of *Ulysses*, BATSE, and the Near Earth Asteroid Rendezvous mission (Cline et al. 1999).

Finally, we note that over 50 bursts were detected by *Ulysses*, WATCH, and in some cases other spacecraft, which will provide error boxes with areas of several hundred arcminutes<sup>2</sup>. Publication of these events is in preparation.

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Fig. 1.— The IPN annuli and the WATCH  $3\sigma$  error circle for GRB 901204.

Fig. 2.— The IPN annuli, the WATCH  $3\sigma$  error circle, and the SIGMA 1, 2, and  $3\sigma$  error contours for GRB910122.

Fig. 3.— The IPN annuli and the WATCH  $3\sigma$  error circle for GRB910219.

Fig. 4.— The IPN annuli and the WATCH  $3\sigma$  error circle for GRB910310. The major contribution to the WATCH error circle uncertainty in this case is the poorly known Granat spacecraft attitude. This systematic error may be underestimated here.

Fig. 5.— The BATSE  $1\sigma$  error circle (left, Meegan et al. 1996), the WATCH  $3\sigma$  error circle (right), and the IPN annuli for GRB911016. The narrow annulus is fully contained within the wider one; its intersection with the WATCH error circle defines the error box.

Fig. 6.— The BATSE  $1\sigma$  error circle (bottom right, Meegan et al. 1996), the WATCH  $3\sigma$  error circle (top left), the IPN annuli (intersecting at grazing incidence), and the SIGMA 1 and  $2\sigma$  error contours for GRB920714.

Fig. 7.— The WATCH  $3\sigma$  error circle, the SIGMA 1, 2, and  $3\sigma$  error contours, and the IPN annuli for GRB920723.

Table 1. Bursts in this catalog

Date	ECT <sup>a</sup>	<i>Ulysses</i>	BATSE	PVO	WATCH	SIGMA	PHEBUS
4 DEC 90 <sup>b</sup>	09:42:52	YES <sup>c</sup>	N/O <sup>d</sup>	YES	YES	N/O	YES
6 JAN 91 <sup>e</sup>	16:39:57	YES	N/O	RI <sup>f</sup>	NO <sup>g</sup>	NO	YES
22 JAN 91	15:13:49	YES	N/O	YES	YES	YES	YES
11 FEB 91	03:25:22	YES	N/O	RI	NO	NO	YES
19 FEB 91 <sup>e</sup>	11:45:24	YES	N/O	YES	YES	NO	N/O
10 MAR 91 <sup>b</sup>	13:02:05	YES	N/O	YES	YES	N/O	N/O
2 APR 91	14:28:15	RI	N/O	RI	NO	YES	YES
17 APR 91 <sup>e</sup>	20:07:32	YES	N/O	YES	NO	YES	YES
17 MAY 91 <sup>b</sup>	05:02:43	RI	NO	YES	YES <sup>h</sup>	YES	YES
16 OCT 91 <sup>b</sup>	11:01:36	RI	YES	RI	YES	N/O	YES
18 OCT 91	05:32:15	YES	NO	YES	NO	NO	YES
22 DEC 91	15:00:10	RI	NO	RI	NO	NO	YES
19 MAY 92	16:31:53	RI	YES	YES	NO	N/O	YES
14 JUL 92	13:04:29	RI	YES	RI	YES	YES	YES

Table 1—Continued

Date	ECT <sup>a</sup>	<i>Ulysses</i>	BATSE	PVO	WATCH	SIGMA	PHEBUS
23 JUL 92	20:03:08	YES	NO	YES	YES	YES	YES
4 OCT 92	14:00:21	YES	NO	YES	YES	NO	N/O

<sup>a</sup>Earth crossing time, UT

<sup>b</sup>Granat attitude missing

<sup>c</sup>Burst was observed in a triggered (high time resolution) mode

<sup>d</sup>Burst was not observable due to, e.g. a data gap, spacecraft not yet launched, etc.

<sup>e</sup>Two possible locations

<sup>f</sup>Burst was observed in untriggered mode, as a rate increase (low time resolution)

<sup>g</sup>Data were available, clean, and complete, but burst was not observed

<sup>h</sup>Burst was observed by WATCH, but could not be localized

Table 2. Error boxes of the bursts in Table 1

Date	Error box corners		Error box center		Error box area, arcmin. <sup>2</sup>	Maximum error box dimension, arcmin.
	$\alpha(2000)$	$\delta(2000)$	$\alpha(2000)$	$\delta(2000)$		
901204 <sup>a</sup>	296.197	37.747	296.483	37.586	43	35
	296.766	37.423				
	296.363	37.668				
	296.602	37.503				
	296.173	37.749				
	296.791	37.421				
910122 <sup>a</sup>	296.918	-70.681	296.756	-70.646	18	10
	296.595	-70.612				
	296.674	-70.660				
	296.838	-70.633				
	297.000	-70.667				
	296.512	-70.626				
910219 <sup>b</sup>	213.731	58.671	213.694	58.688	7.3	4.7
	213.657	58.705				
	213.723	58.710				
	213.665	58.666				
	213.701	58.649				
	213.687	58.727				



Table 2—Continued

Date	Error box corners		Error box center		Error box area, arcmin. <sup>2</sup>	Maximum error box dimension, arcmin.
	$\alpha(2000)$	$\delta(2000)$	$\alpha(2000)$	$\delta(2000)$		
910310 <sup>b</sup>	184.358	7.266	184.304	7.196	63	38
	184.249	7.125				
	184.198	6.921				
	184.405	7.462				
	184.424	7.480				
	184.178	6.901				
910402 <sup>a</sup>	77.612	13.611	77.629	13.690	35	14
	77.647	13.768				
	77.598	13.675				
	77.661	13.704				
	77.631	13.571				
	77.627	13.810				
910517 <sup>a</sup>	150.475	-42.876	150.602	-42.780	236	92
	150.730	-42.693				
	149.659	-43.107				
	151.546	-42.447				
	151.545	-42.447				
	149.659	-43.107				
911016 <sup>c</sup>	297.996	-5.386	298.137	-4.811	530	70
	298.151	-4.220				
	298.148	-5.205				
	298.251	-4.434				

Table 2—Continued

Date	Error box corners		Error box center		Error box area, arcmin. <sup>2</sup>	Maximum error box dimension, arcmin.
	$\alpha(2000)$	$\delta(2000)$	$\alpha(2000)$	$\delta(2000)$		
911018 <sup>a</sup>	5.468	31.957	6.009	31.658	50	74
	6.542	31.353				
	5.401	31.992				
	6.608	31.316				
	6.486	31.397				
	5.526	31.914				
911222 <sup>a</sup>	87.139	13.137	87.084	14.062	200	118
	87.005	14.938				
	87.159	13.274				
	87.023	15.111				
920519 <sup>a</sup>	321.422	44.221	321.254	44.137	21	23
	321.485	44.228				
	321.024	44.046				
	320.087	44.053				
920714 <sup>d</sup>	220.826	-30.721	220.857	-30.610	36	20
	220.897	-30.506				
	220.848	-30.607				

Table 2—Continued

Date	Error box corners		Error box center		Error box area, arcmin. <sup>2</sup>	Maximum error box dimension, arcmin.
	$\alpha(2000)$	$\delta(2000)$	$\alpha(2000)$	$\delta(2000)$		
920723 <sup>a</sup>	287.128	27.216	287.142	27.232	0.9	3.2
	287.155	27.248				
	287.126	27.210				
	287.157	27.255				
	287.148	27.249				
	287.135	27.215				
921004 <sup>e</sup>	219.244	34.180	219.236	34.180	3.25	8.25
	219.261	34.115				
	219.211	34.246				
	219.228	34.180				

<sup>a</sup> *Ulysses* /PHEBUS/PVO triangulation error box

<sup>b</sup> *Ulysses* /PVO/WATCH triangulation error box

<sup>c</sup> *Ulysses* /BATSE and *Ulysses* /PVO annuli intersect at grazing incidence; error box is defined by the four intersections of the *Ulysses* /BATSE annulus and the WATCH error circle

<sup>d</sup> *Ulysses* /BATSE and *Ulysses* /PVO annuli intersect at grazing incidence; the annuli in turn graze the WATCH error circle. The error box is defined by the three intersections of the *Ulysses* /BATSE annulus and the WATCH error circle

<sup>e</sup> *Ulysses* /PVO/WATCH triangulation error box